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Classification of TRIZ Techniques Using a Cognition-Based Design Framework

Dr. Philip Samuel[a]*, and Dr. Michael Ohler[b]

[a]*BMGI, Chief Innovation Officer, 1200 17th St., Suite 180, Denver, CO, 80202 USA*
[b]*BMGI, European Practice Leader, Brachvogelweg 23, Hamburg, 22547 Germany*

Abstract

The role of the Theory of Inventive Problem Solving (TRIZ) techniques within engineering design is examined through the lens of Cognition- based Design (CBD). The paper aims to answer some of the questions sought by the design community at large and to provide some directions for scholars and practitioners on how TRIZ techniques can be applied during various stages of the design process. The CBD framework is based on a systems-view that integrates core principles coming from traditional engineering design with fundamental concepts as they are used in cognitive psychology and other fields related to cognition (e.g., problem solving, creativity, and learning theory).
The paper provides the details of the proposed cognition-based classification scheme for TRIZ techniques. This is illustrated with the help of the CBD framework. The classification scheme is based on three components: (1) the stage of the design process in which TRIZ techniques are applied and the primary cognitive function supported by the technique; (2) the cognitive level required for mastery of the technique; and (3) the cognitive style simulated through the technique. The aim of this classification scheme is to help design practitioners and TRIZ students make better choices about the techniques they will use, based on the challenges of the given design opportunity, rather than choosing only those techniques they are familiar with. Recommendations are given for making use of the new classification scheme and guidelines for future research. That research can also identify potential loopholes in the problem solving process and techniques, as they are currently available to the designer.

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Keywords: Cognition-Based Design; Adaption-Innovation Theory; TRIZ Techniques; Cognitive Style

* Corresponding author. Tel.: +1-480-216-0314; fax: +1-775-766-7789.
E-mail address: Phil.Samuel@bmgi.com

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1. Introduction

Although most practitioners of engineering design are familiar with the Theory of Inventive Problem Solving or TRIZ, many engineers and designers outside the TRIZ community seek a better understanding of exactly when and how TRIZ can be used within the design process [1,2,3,4,5]. This paper aims to provide some direction for scholars and practitioners by examining TRIZ techniques and its potential role within engineering design and related problem solving through the lens of problem solving and cognition.

The value of operating from this broad perspective is that it facilitates a better understanding of the enabling and limiting features of TRIZ techniques and their application within the design process. In addition, this perspective supports an exploration of some of the underlying cognitive aspects of design. This will be useful to examine both in general terms and when using TRIZ as a specific example. This understanding will help explain why particular TRIZ techniques are more appealing to some designers than others. It also highlights the importance of recognizing and appreciating the value of cognitive diversity within design teams.

2. Cognition-Based Design

In order to properly utilize the underlying structure and rationale of the TRIZ technique classification scheme described in this paper, it is important to describe the general design framework that lies behind it. This framework, called Cognition-Based Design (CBD), is based on a systems-view that integrates core principles from traditional engineering design with fundamental constructs from cognitive psychology and other fields related to cognition (e.g., problem solving, creativity, and learning theory). At a fundamental level (see Figure 1), the CBD framework incorporates an adapted version of the original "4P" model by Rhodes [6], which includes the People, Process, Product, and Press (Environment) of design, along with the original design Problem (also known as "Problem A" [7].

One way to manage Person-Problem cognitive gaps in a design context is to use techniques in order narrow the distance between a designer's usual way of thinking and the type(s) of thinking required to resolve a given Problem A. For example, a designer whose capacity for identifying the contradiction is low might learn the basic contradiction modeling technique to help bridge this (level) gap. Or, a designer who tends to think tangentially may need to apply techniques that help him or her to "stay focused" (which is a different style) in order to solve a particular problem. Once again, we recognize the need for a systematic way to characterize TRIZ techniques so that the appropriate choices can be made. We turn now to our development of such a classification scheme.

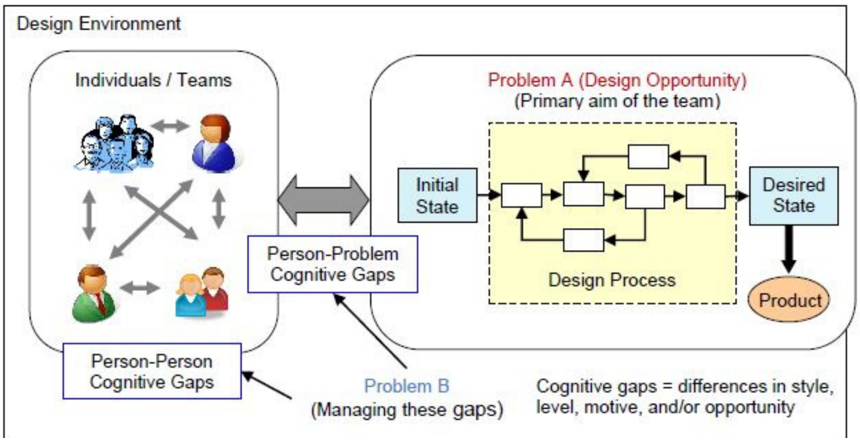

Fig. 1. Cognition-Based Design Framework.

3. A Cognition-Based Classification Scheme for TRIZ Techniques

Utilizing the CBD framework described above, we have developed a classification scheme for TRIZ techniques in three directions as described below:

1. The stage of the design process in which TRIZ techniques are applied and the primary cognitive operation supported by this technique (divergent vs. convergent thinking)
2. The cognitive level required for a mastery of the technique (low to high)
3. The cognitive style simulated through the technique (more adaptive to more innovative).

We will now describe each of these classification schemes in some detail and illustrate it with the help of a set of commonly used TRIZ techniques.

3.1. Classification of Techniques by Primary Cognitive Operation and the Stage of the Design or Problem Solving

We start our discussion with the "Process" aspect of design, in which we consider (first) "where we are" in the design process and (second) then whether we are "fanning out" with multiple options or "focusing in" by narrowing down our options for the design challenge or solutions. In other words, design techniques can be categorized in terms of the stage of the design *process* in which they are most appropriately applied *and* in terms of the *primary cognitive operation* (divergent vs. convergent thinking) they support within that stage. The stages involved in the engineering design process and in TRIZ problem solving are discussed extensively in the literature [8,9,10,11,12], so they are not reviewed here.

Table 1. Classification of Techniques by Primary Cognitive Operation.

Technique	**Process Stage**	**Primary Cognitive Operation**
Ideality	Problem formulation	Divergent operation
Ideal Final Result	Problem formulation	Convergent operation
5 Whys	Problem formulation	Convergent operation
Abstraction	Problem formulation	Convergent operation
Su-Field Modelling	Problem formulation	Convergent operation
Contradiction Modelling	Problem formulation	Divergent operation
Many (Smart) Little People Modelling	Problem formulation	Divergent operation
Inventive Resources	Problem formulation	Divergent operation
Nine Screens	Problem formulation	Divergent operation
Functional Analysis	Problem formulation	Convergent operation
Time of Conflict	Problem formulation	Convergent operation
Zone of Conflict	Problem formulation	Convergent operation
40 Inventive Principles	Solution generation	Divergent operation
Separation Principles	Solution generation	Divergent operation
Scientific Effects	Solution generation	Divergent operation
76 Standard Solutions	Solution generation	Divergent operation
Evolutionary Trend Predictions	Solution generation	Divergent operation
ARIZ	Problem formulation Solution generation	Divergent operation Convergent operation

Every stage of the design process is associated with two fundamental cognitive operations called divergent operation and convergent operation, which have their roots in problem solving research [13,14]. The divergent thinking operation involves searching for ideas and increasing one's options through the elaboration of the design problem, a redefinition of the problem, and exploring, connecting, or combining potential ideas and solutions. In contrast, the convergent thinking operation involves evaluating ideas and narrowing or reducing one's options through the imposition of value judgments, by exploiting the information available about the ideas, or by prioritizing and selecting.

For both, divergent and convergent thinking, the resulting ideas and solutions may fall inside, at the edges of, or outside the relevant technical domain and paradigm [14,15]. We make this statement to ensure that divergent thinking is not considered synonymous with "out of the box" thinking nor is convergent thinking synonymous with "inside the box" thinking. All designers can both diverge and converge in their thinking and do so at different cognitive levels and with different preferred styles; these operations lead to solutions throughout the design space. Divergence and convergence will lead to slightly different interpretations when put into the context of different design stages. Divergent operation during problem formulation involves generating multiple options for the design opportunity or problem formulation, especially by reframing the challenge in many different ways. In contrast, convergent operation during problem formulation involves choosing the design challenge to focus on. Divergent operation during the solution generation stage involves generating multiple ideas to address the design challenge, while convergent operation during this stage involves narrowing down the number of potential solutions to pursue. These variations of contextual interpretation are important when it comes to identifying the techniques that support each cognitive operation in different process stages.

Combining the "process stage" perspective with the primary cognitive operation supported by a particular technique, we can provide design students and practitioners with a roadmap for choosing the most appropriate techniques based on these two components. Here, we have analyzed a selection of TRIZ techniques commonly used in practice (see Table 1) to illustrate how this portion of the new classification scheme works. For example, "5 Whys", is a common technique used within and outside the TRIZ community, initially during the problem formulation stage. It is used to describe the problem and identify the root causes of the problem to be solved. Initially the "5 Whys" could lead to several possible root causes of the problem (diverging in the beginning), but the analysis would eventually reduce the options to one or more root causes that are appropriate for seeking solution (thus aiding convergence operation at the end). "Functional Analysis" also operates in a similar fashion. This technique is used to list the functions (useful, harmful, insufficient, excessive, etc.) performed by the system components so that root cause of the problem can be isolated. Such an analysis should lead to a smaller set of problem options (thus categorized as convergent operation). On the other hand, "Nine Screens" can be used to reformulate the problem in nine different ways using past, present, future, sub-system, system, and super-system operators. As a result, this technique enables the user to generate multiple options for the design opportunity. We have thus categorized this technique as aiding the divergent operation.

In a similar fashion, we have categorized the solution generation techniques as well in terms of aiding convergent and divergent operations. For example, one can use "40 Inventive Principles" to generate multiple solutions for the design challenge at hand. However, when "40 Inventive Principles" is used in lieu of general brainstorming, the technique may generate fewer sets of ideas in comparison. This should not be confused as convergent operation. Both techniques generate multiple ideas to solve the design challenge. Hence we have categorized "40 Inventive Principles" technique as aiding divergent operation during the solution generation stage. However, a technique such as "Multivoting" or "Pugh Matrix" can be used to reduce the number ideas by evaluating them against certain decision criteria. These techniques, typically not listed as TRIZ techniques, aid the convergent operation during the solution generation phase.

3.2. Classification of Techniques by Cognitive Level and Cognitive Style

Having discussed the classification scheme for the "Process" aspect, we now move to the second and third aspects of our classification scheme, which highlight the cognitive diversity of the designer as an individual (i.e., the

“Person”). These include the cognitive level required for the mastery of a technique and the cognitive style simulated through the use of that technique.

The distinction between cognitive level and cognitive style has been discussed by many scholars, both in a general context [14,16] and in the specific contexts of design [17,18,19]. In general, cognitive level is a unipolar construct that relates to an individual’s thinking capacity, both potential (like intelligence, aptitude, or talent) and manifest (like extant knowledge, skill, or experience). The manifest level can be measured in terms of type (i.e., domain – discipline, area of study) and degree (i.e., amount – novice, expert). Cognitive style is defined as a “strategic, stable characteristic – the preferred way in which people respond to and seek to bring about change”, which includes the formulation as well as solution of problems [14]. As such, cognitive style is a bipolar construct that is independent from level; it also has multiple dimensions, including Adaption-Innovation (A-I) [14,15].

Cognitive level is often readily understood by students and practitioners of design alike, even if this formal term is not used. Often, students and instructors are in the habit of assessing themselves and others in “level” terms – i.e., “how much of an expert” someone is at solving a design challenge, “how much” they have achieved in a particular “area of study” in which they excel, etc. We apply this thinking to TRIZ techniques across different stages of the design process, using the following scale to reflect the level required for their mastery:

- Level 1 = very easy to master
- Level 2 = easy to master
- Level 3 = mid-level difficulty to master
- Level 4 = hard to master
- Level 5 = very hard to master.

The same selection of techniques that appeared in Table 1 are mapped according to this level metric below (see Table 2), after we have discussed the classification of techniques according to their simulated cognitive style.

As noted before, there are many dimensions of cognitive style just like the different dimensions of cognitive level. For our study, we focus on the dimension of cognitive style known as Adaption-Innovation (A-I) [14], as it was specifically developed and validated in the context of problem solving, making it highly suitable for the design process. The A-I cognitive style is defined on a bipolar continuum that ranges from high Adaption to high Innovation (see Figure 2).The key distinction to differences between more adaptive and more innovative individuals is related to their preferred way of managing structure in problem solving [14,16,17]. Individuals who are more adaptive prefer to operate with more structure and with more of this structure consensually agreed. In contrast, individuals who are more innovative prefer to operate using less structure and are less concerned about achieving consensus around that structure as they proceed; indeed, they are more likely to want to change consensus than to conform to it fully. One way of summarizing these basic differences is to say that the more adaptive prefer to solve problems using the rules, while the more innovative prefer to solve problems despite the rules [14,17,18], however such “rules” might be defined and implemented. One’s preferred cognitive style is considered to be genetically determined [20, 21] and research has indeed shown that it is stable over one’s lifetime [22].

Within this simple description, it is critical to remember that we are dealing with a continuum of cognitive style, not a dichotomy of “types” – hence the descriptors “more adaptive” and “more innovative”, as befits a continuous model. In addition, it is important to note that no particular position along this continuum is considered ideal overall; every variation of cognitive style has its advantages and disadvantages when the current problem (rather than anyone’s personal preference) is the focal point. These differences in cognitive style produce distinctive patterns of behaviour, although an individual can behave in ways that are not preferred (i.e., that are not in accord with his/her style) when sufficient motive is provided. This non-preferred behaviour is called coping behaviour [14], and it comes at an extra psychological cost; that is, all behaviour requires effort, but coping behaviour requires more of it.

In summary, the more adaptive prefer more structure during the design process or when problem solving in general, with more of that structure consensually agreed, while the more innovative prefer less structure and are less concerned about achieving consensus around the structure they use. In other words, the more adaptive prefer to work with and within existing guidelines or rules in order to achieve solutions that improve a system, whereas the more innovative are more likely to feel constrained by rules, preferring instead to operate at the edges of or even across structures in order to solve problems differently. Every engineer or designer is more adaptive when compared to some individuals and more innovative when compared to others [14].

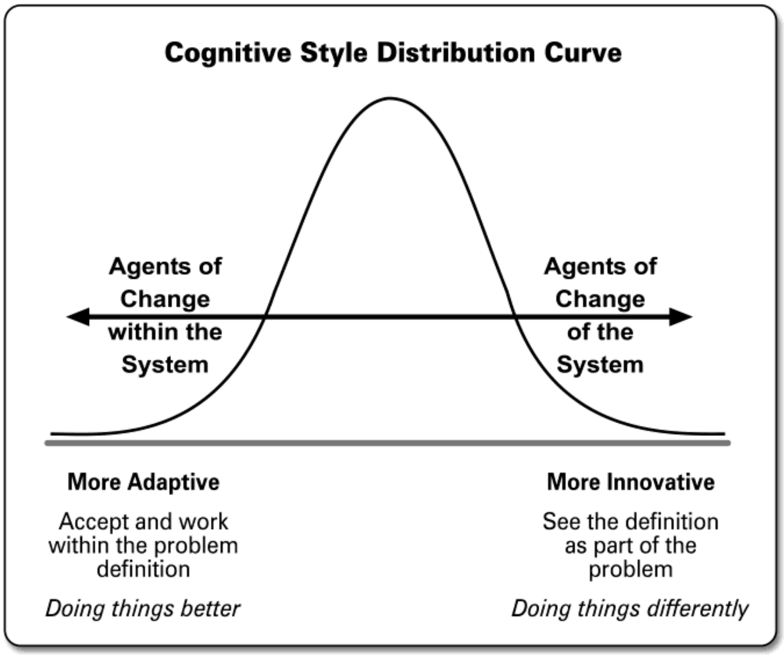

Fig. 2. The Adaption-Innovation Continuum of Cognitive Style

In light of these descriptions, techniques can be classified in terms of the style they simulate. When a technique is using the strategy deployed by the more adaptive brain, we categorize that technique as simulating the more adaptive style and vice versa. The techniques that simulate a more adaptive style can be used to help designers and engineers generate and work with ideas that support and refine the structure of a system (making it more efficient), while those that simulate a more innovative style can be used to help designers and engineers generate and work with ideas that loosen or reframe the system's structure. Clearly, many styles of thinking are required within any complex design effort, so it is important for designers to be able to choose techniques wisely and to build a "toolbox" of diverse techniques that can be used to meet different aims in a variety of circumstances. In addition, based on a designer's own cognitive level and cognitive style, different amounts of individual coping behavior (i.e., behavior away from one's own cognitive preference) will be required depending on which technique is used.

To support the integration of all three directions into a single classification scheme, Jones [23] maintains that general problem solving techniques can be classified into those that aid convergent and divergent thinking operations, respectively, while Lopez-Mesa, et al. [18] suggest that they can be further classified into those that simulate more adaptive and more innovative styles. In other words, problem solving techniques can be classified as innovative divergent techniques or adaptive divergent techniques, or as innovative convergent techniques or adaptive convergent techniques. However, as with the continuum of cognitive style for individuals, this classification also spans across a spectrum of simulated styles, with some techniques being more adaptive or more innovative than others, rather than "bunched" into two piles or categories.

In general, adaptive divergent techniques will help a designer generate a sufficient number of ideas through a process of successive refinement (e.g., 40 Inventive Principles) and systematic frameworks (e.g., 76 Standard Solutions). Innovative divergent techniques enable the proliferation of ideas through concept re-structuring and increased boundary spanning (e.g., Evolutionary Trend Predictions), as well as through abstraction and analogies (e.g., Separation Principles). Adaptive convergent techniques reduce or narrow the spectrum of ideas through detailed analysis (often quantitative in nature) of the ideas (e.g., Monte Carlo simulations) and through more structured processes (e.g., Control Charts). Innovative convergent techniques enable the evaluation and selection of ideas through the analysis of approximate or soft information (e.g., Pugh Matrix) and using more qualitative assessments (e.g., Multi- voting).

To illustrate the second and third components of the proposed classification scheme, a set of TRIZ techniques selected and classified according to process stage and cognitive operation in Table 1 are now presented in Table 2 where they are organized in terms of the range of cognitive styles they simulate and the level required for their mastery. Note how, in general, techniques of different levels and styles span across the stages of the design process.

Table 2. Preliminary Classification of TRIZ Techniques by Level and Style

Mastery Level	More Adaptive Style				More Innovative Style
5	ARIZ 76 Standard Solutions				
4	Substance Field Modelling 40 Inventive Principles	Scientific Effects Contradiction Modelling		Evolutionary Trend Predictions	
3	Time of Conflict Zone of Conflict	Functional Analysis Subversion Analysis	Inventive Resources Nine Screens	Separation Principles	Ideal final Result
2			Many (Smart) Little People Modelling	Ideality	
1		5 Whys		Analogy	Abstraction

4. Remaining Questions and Future Work

The classification scheme described in this paper is based on sound theory and practice in related fields. However, at present, the mapping of techniques is based mostly on discussions, criticism and evaluation among the authors and a few other practitioners of design and TRIZ. We will need the feedback from the community at large of engineers and design practitioners in order to confirm our preliminary classification and to evaluate an expanded list of TRIZ techniques.

We have designed and are currently in the process of validating a psychometric instrument that can be used to classify various design and TRIZ techniques using the CBD framework. The instrument contains several questions that relate to cognitive level and cognitive style as it is applied to a particular technique. For example, when a designer is asked to rate the level of agreement for a technique such as “40 Inventive Principles” on a statement such as “a first-time user will find this technique easy to learn”, it is measuring the cognitive level required to master that technique. Similarly, when a designer is asked to rate the level of agreement for the same technique on a statement such as “this technique leads a user to ideas/solutions outside the current paradigm”, it is measuring the degree of innovative (cognitive) style that the technique simulates. Another statement such as “the manner in which this technique is used is consistent and predictable” or “this technique follows a logical, step-by-step approach” measures the degree of adaptive (cognitive) style that the technique simulates.

The first phase of the research involves the exploration, development and validation of the instrument focusing on the classical test theory approach to psychometric validation including stability, reliability (internal consistency, test-retest, inter-rater), validity (construct, known-groups), and ability to detect change (responsiveness). Once validation work is completed, we intend to use the instrument to classify TRIZ and other techniques using the CBD framework described in the paper.

Due to space and other practical limitations, we selected only a handful of TRIZ techniques for analysis in this paper. As a result, our tables clearly have gaps in them. In analyzing and classifying a larger number of TRIZ techniques (as described above), we will need to remain cognizant of how well the cognitive design space represented by Tables 1 and 2 is being “covered” by the techniques that already exist. In other words, we want to be sure that sound techniques are available for every combination of process stage, cognitive operation, cognitive level, and cognitive style. If a technique cannot be found to fill a particular position within the tables, then new techniques will have to be created or existing techniques adapted to fill that void.

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